Solid-State Power Generation and Cooling Micro/Nanodevices for Distributed System Architectures

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by

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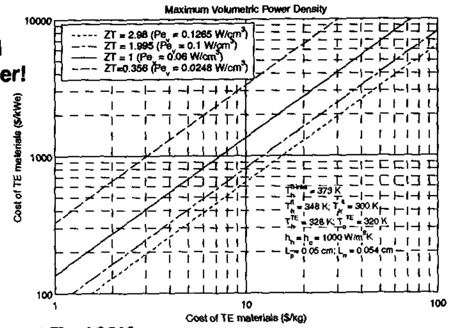
Advanced Thermoelectric Devices

- Even with a small improvement in ZT, TE applications could be extended to new fields
  - **Sometimes, cost or specific power and not efficiency is the important parameter!**
- Power generation
  - **Waste heat recovery**
    - **Bottoming or topping cycles**
  - **microdevices**
    - **for cryobots, hydrobots...microbots**
    - **low power electronic devices**



- Cooling
  - **Cryocoolers at T< 100K**
  - **microcoolers**
    - **For integration in thermal management packages**
- Sensors
  - **Using temperature variations linked to radiation, electrical energy...**
    - **Integration with CMOS technology, MEMS techniques**

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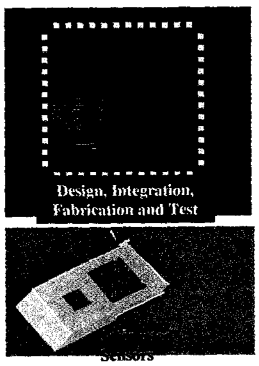
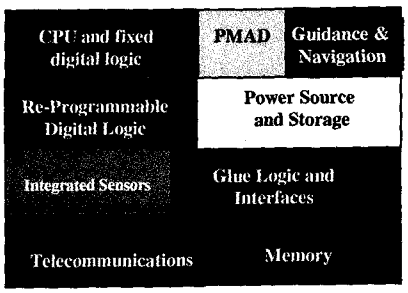
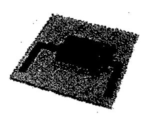
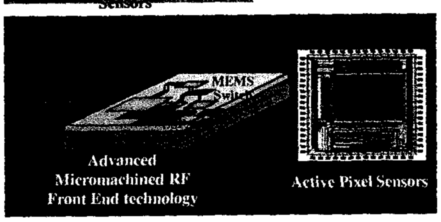
System On A Chip Technology

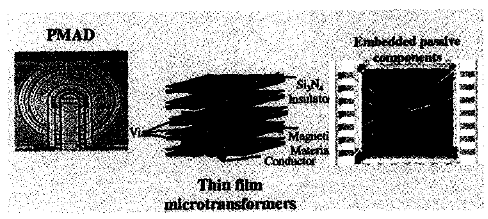






On-Chip Power Source





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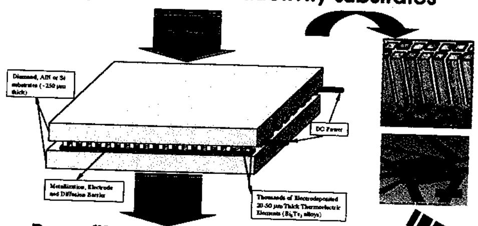
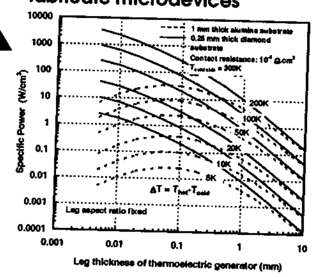
TE Micro/Nanodevices at JPL

- Objective: Develop thermoelectric micro/nanodevices using integrated-circuit type fabrication processes, electrochemical deposition/CVD and high thermal conductivity substrates



- Technical Approach
  - Synthesize 1-100 μm thick thermoelectric elements using electrochemical deposition/CVD
    - Study new materials and low dimensional structures (nanowires)
  - Develop stable metallization to diamond, AlN, Si substrates
  - Develop novel techniques to fabricate microdevices



- Benefits and applications
  - High specific power (W/cm³) for cooling, and electrical power generation
    - Ability to generate high voltages even under low ΔT, heat flux conditions
  - High degree of integration between thermal management/power and electronics
    - System-on-a-chip concept
    - Co-location of sense, actuate, command, power, communicate and thermal management functions
    - Use for power electronics, distributed sensor networks

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Thermal Management

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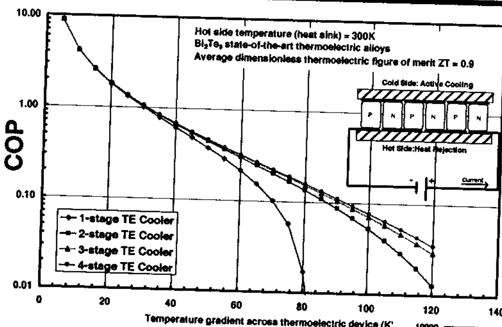
Thermoelectric Cooling

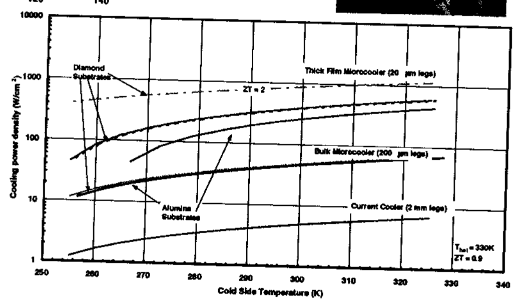


- COP inversely proportional to ΔT and increases with increasing ZT
- Devices can be designed to function at maximum power or maximum efficiency
- TE Device is scalable

$$COP = \frac{Q_{cold}}{P_{el}} = \frac{S_{pn}T_{cold}I - \frac{1}{2}RI^2 - K(T_{hot} - T_{cold})}{S_{pn}(T_{hot} - T_{cold})I + RI^2}$$

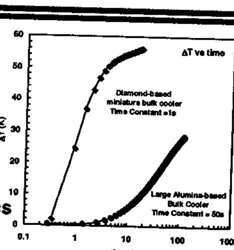
$$Q_{cold}^{max} = \frac{A}{l}\left[\frac{1}{2}\frac{S_{pn}^2 T_{cold}^2}{\rho_{pn}} - \lambda_{pn}(T_{hot} - T_{cold})\right]$$

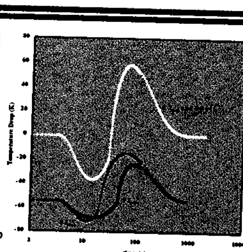
$$ZT = \frac{S^2 T}{\rho \lambda}$$

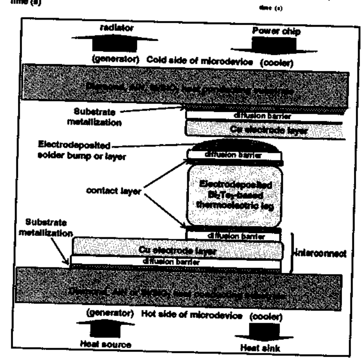


Thermoelectric Microdevices

- Miniaturized TE devices
  - High power densities
    - Both cooling, electrical
    - High voltage operation
  - High degree of integration
    - With electronics, optoelectronics
  - Fast response time
    - "ms" instead of "s" to reach ΔT_{max}
    - Pulse operation can be considered
- Miniaturized configuration at JPL
  - Vertically integrated module
    - Higher heat losses for planar devices
  - Key differences with bulk devices
    - Thousands of p-n junctions
    - High thermal conductivity substrates
    - Thermally stable metallizations
    - Electrochemical deposition
      - Thick films of semiconductors, metals
    - Integrated circuit processing techniques

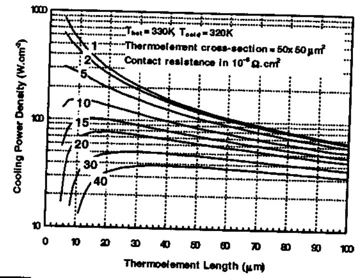


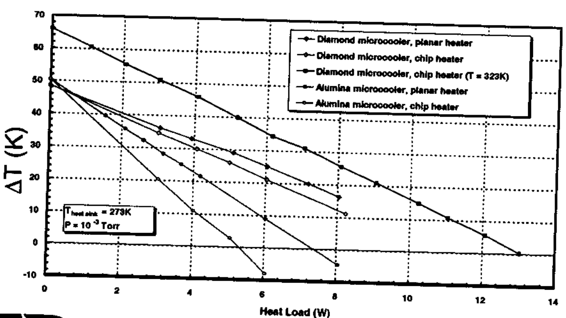




Thermoelectric Microdevices Issues

- Miniaturization issues to be considered
  - **Electrical contact resistance**
    - **The shorter the leg, the more critical the electrical contact resistance**
    - **Develop high quality metallization and bonding schemes**
  - **Mechanical integrity**
    - **Thermal stress due to large temperature differentials, non-uniform heat spreading**





- **Thermal resistance**
  - **Due to substrates, packaging**
    - **Importance increases as leg thickness decreases**
  - **High heat fluxes**
    - **Heat spreading**
  - **Heat transfer is key**
  - **Use high thermal conductivity substrates such as:**
    - **Diamond, AlN, Si/SiO$_2$**

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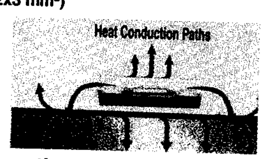
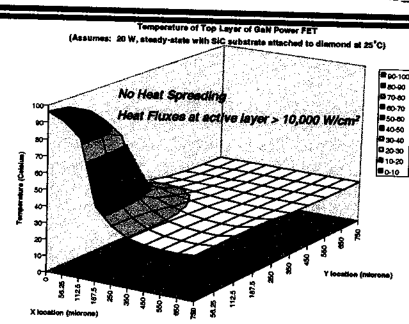
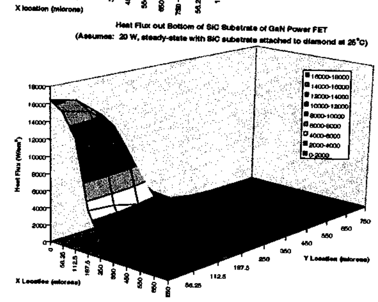
Thermal Management of High Power Electronics

- **20W GaN device/die/diamond-based cooler/heat sink**
  - Next generation solid state power amplifier
- **Results indicate chip operating temperature too high**
  - Mostly due to temperature gradient across chip substrate
  - Active area (200x200 μm^2) much smaller than SiC die (2x3 mm^2)



- **Requires active cooling**
  - Cool below ambient back of the power chip
    - So that active electronic layer to remain below 100°C
    - Single-stage/multi-stage thermoelectric device to offset chip ΔT
  - Critical that cooler be as close to power producing portion of device
    - Attach cooler to die using high thermal conductivity materials
    - If device much smaller than cooler then use diamond heat spreader
  - Additional heat sinking technique required
    - To conduct heat away from cooler hot side
    - Where it can be safely dissipated





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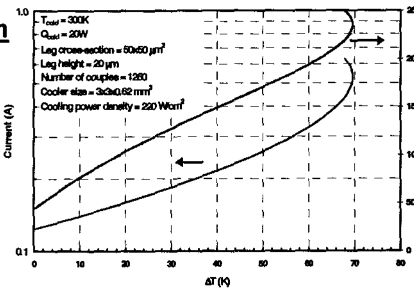
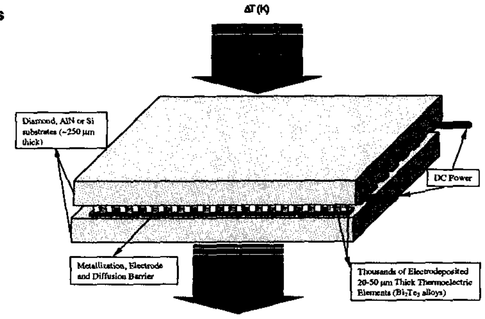
High Power TE Microcooler

TE microcoolers: a potential configuration

- Cooling of power chip dissipating $20W_{th}$
  - Power amplifier
    - Active junctions size: 200x300 μm^2
    - SiC die size: 2x3 mm^2
  - Thermoelectric microcooler
    - Cooler dimensions: 3x3 mm^2 cross section, 0.63 mm thick
    - 1250 thermocouples
    - leg size: 50x50 μm^2 cross-section, 20 μm thickness
  - Cooling performance at 30K ΔT:
    - Power input: 21.1 W
    - Heat rejected: 41.2 W
    - Current: 0.32 A and voltage: 66 V
  - Cooling performance at 50K ΔT:
    - Power input: 50.2 W
    - Heat rejected: 70.2 W
    - Current: 0.48 A and voltage: 104V
  - Lower voltage, higher current, higher ΔT possible
    - Internal parallel connections, multistage configurations





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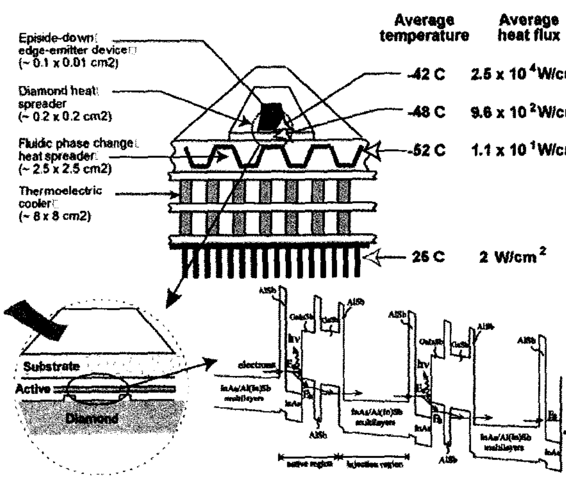
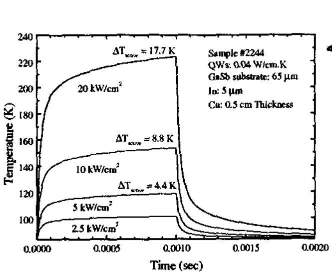
Cooling for Low-Power Optoelectronics

- Mid-IR Lasers
- Major Heating Problem!!!
  - > 1000 layers and hetero-interfaces
  - Superlattice structure has much poorer thermal conductivity
  - Active region could be much hotter (>> 100 ºC) than the heat sink





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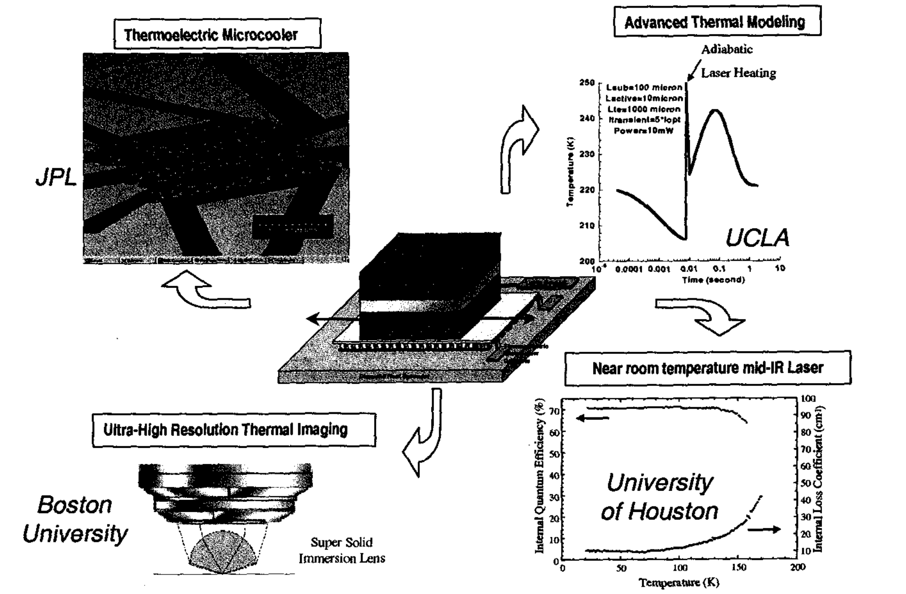
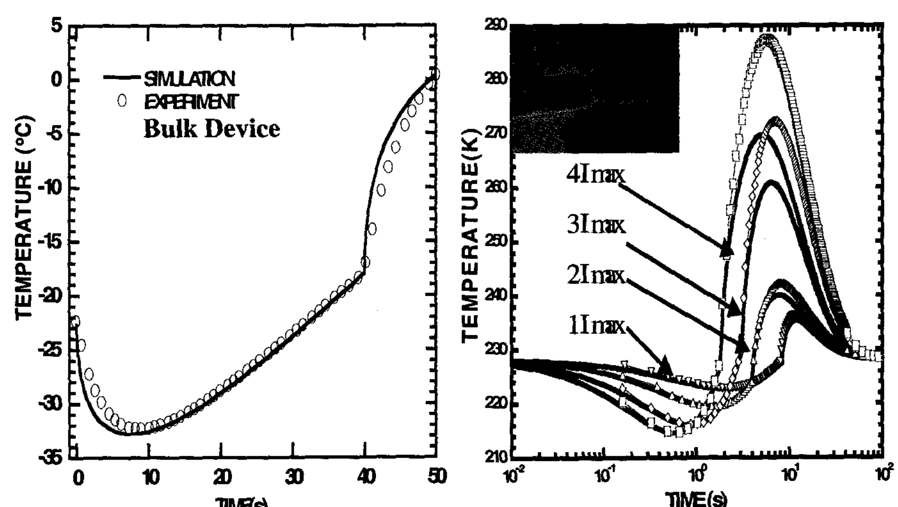
Monolithically Integrated TEMC/Mid-IR Lasers



TRANSIENT THERMOELECTRIC EFFECTS

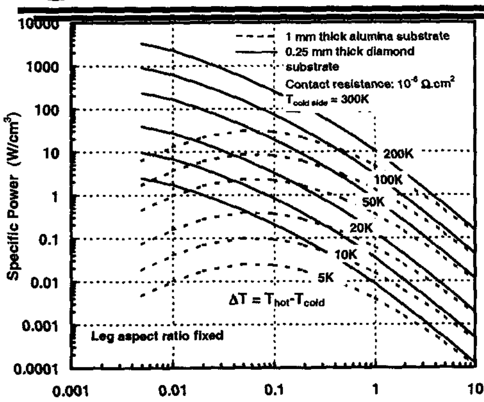


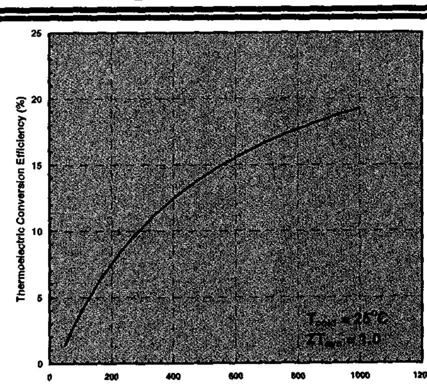
23 mm Leg Length

6 mm Leg Length

Power Generation

Thermoelectric Power generation





$$\eta = \frac{P_{el}}{Q_{hot}} = \frac{R_{Load} I^2}{S_{pn} T_{hot} I - \frac{1}{2} R I^2 + K(T_{hot} - T_{cold})}$$

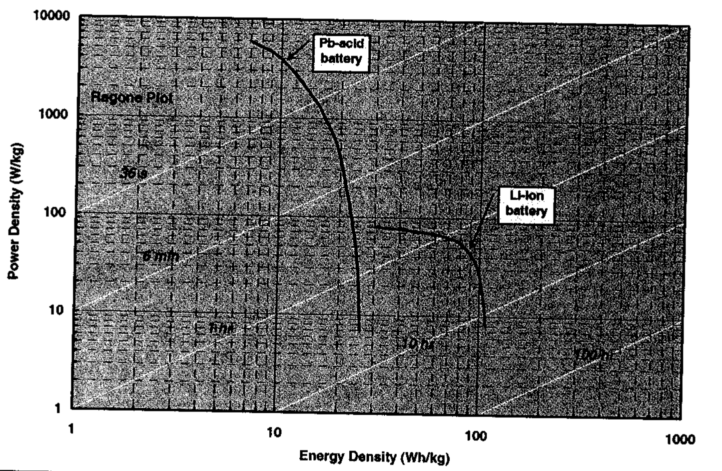
$$P_{el}^{\max} = \frac{A}{l}\left[\frac{1}{4}\frac{S_{pn}^2 (T_{hot} - T_{cold})^2}{\rho_{pn}}\right]$$

$$ZT = \frac{S^2 T}{\rho \lambda}$$

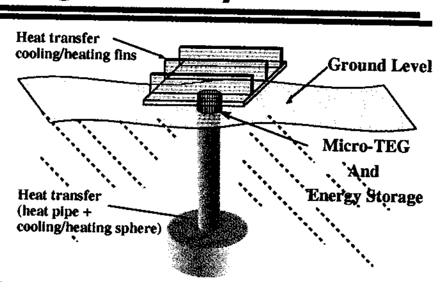
- Energy conversion limited by Carnot efficiency and increases with increasing ΔT, ZT
- Devices can be designed to function at maximum power or maximum efficiency
- Thermoelectric device is scalable

Need for Advanced Mobile Power Sources

- High specific power and/or high specific energy requirements
  - Thermoelectrics could contribute to solutions; for example:
    - High efficiency TE systems using high temperature source and/or hybrid conversion system
    - High specific power microdevice or high specific energy energy harvesting device

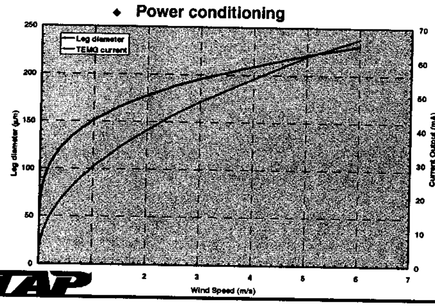


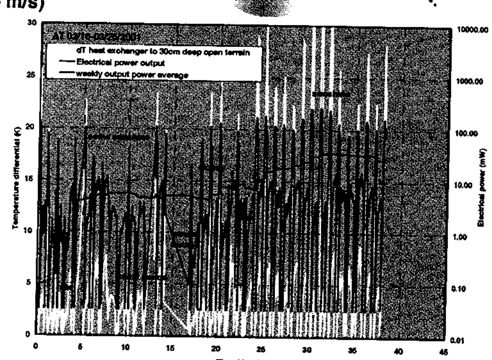
Energy Harvesting Concept



Environmental heat source development

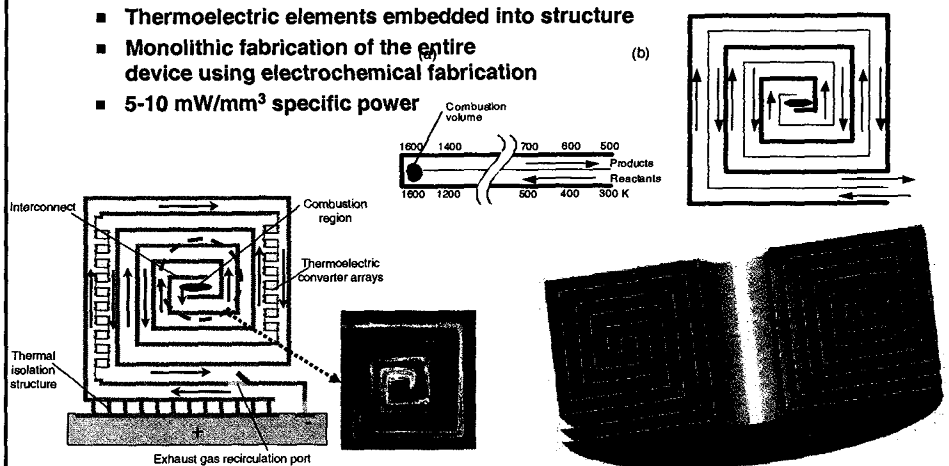
- Use of natural temperature gradients
  - To provide 10-100s of mW output
    - Can be as small as 1K
- Potential system:
  - ΔT air/soil during day, night
  - Calculations show feasibility of concept for very low wind speed values (0.5 to 0.75 m/s)
  - Operating current and voltage can be tailored by using parallel strings of TE legs
    - Power conditioning





MicroFire Power Source

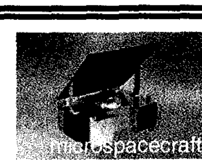
- USC/MemGen Inc./JPL collaboration
  - "Swiss roll" heat recirculating burner with toroidal 3-D geometry
  - Thermoelectric elements embedded into structure
  - Monolithic fabrication of the entire device using electrochemical fabrication
  - 5-10 mW/mm^3 specific power



3-D toroidal Swiss roll microcombustor/generator

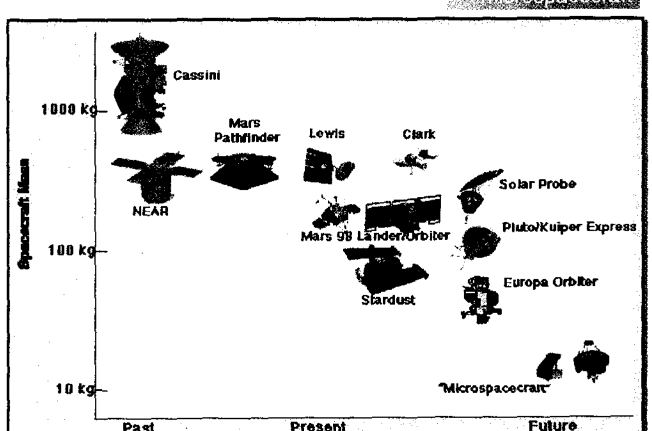
Drive for Increased Miniaturization

Micro/nano sciencecrafts for deep space exploration



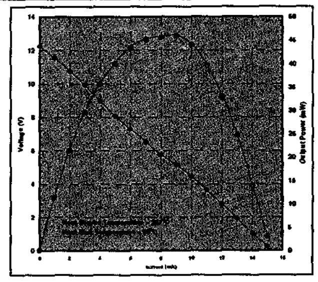
Increased miniaturization

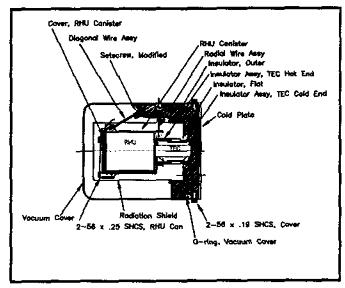
Increased integration of sciencecraft functions and components



Milliwatt Power Source (MWPS)

- MWPS: a miniature radioisotope thermoelectric generator
  - 1.1 W RHU (Radioisotope Heater Unit, 26 mm Ø x 32 mm long, 40 g weight)
  - 18x18 thermopile array of Bi_2Te_3 thermoelectric elements
    - 7.4 x 7.4 x 23 mm dimensions, Thot = 225°C, Tcold = 25°C
  - Packaging canister
    - Optimized design being developed by Hi-Z technologies
- 5.5 V_{DC}, 45 mW electrical power output, 350 g overall weight
  - Can be combined with rechargeable batteries, or ultra-capacitors for low duty cycle, higher power output
  - Design could be modified to accommodate two or more RHU
    - Will improve specific power by at least 30%





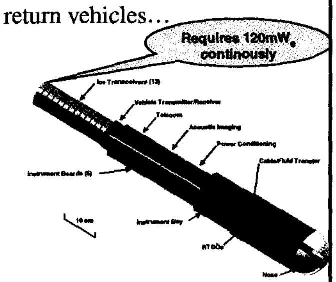
Micropower for Outer Planets missions

⇨ **Outer Planets exploration activities**

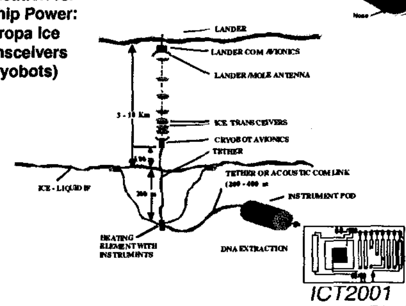
- Through ice, water, cryogenic liquids, hot gases, high g loads, moderate to high radiation
- Such as for Europa landers, Titan explorers, Comet sample return vehicles…

⇨ **Need for miniaturized robust power sources**

- To enable/prolong planetary exploration, to permit novel/more science measurements
- To enable development of novel miniaturized autonomous probes such as drop-off penetrators, weather microstations, communication relay devices, etc…

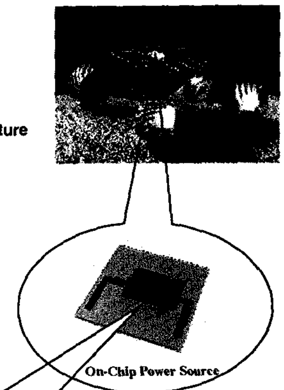


Potential Application for On-chip Power: Europa Ice Transceivers (cryobots)



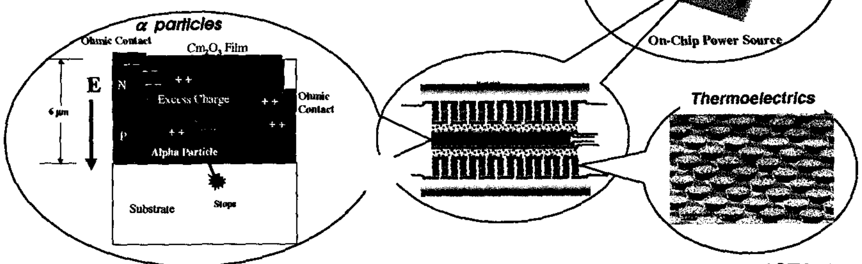
On-Chip Power Source

- **Need for highly miniaturized power sources**
  - NASA missions call for use of a number of small, compact vehicles for exploring a great variety of environments
    - Cold, hot, high g, high radiation, no sun light...
    - Long life characteristics highly desirable (includes shelf life)
  - Ultimate goal is to have power integrated within SOAC-type chip architecture
    - Enabling technology for a variety of sensors and other electronic, optoelectronic components
  - Do better than electrochemical batteries!



<u>Novel Technology Target Performance vs SOA</u>:

System	SiGe RTG	MWPS	**On-Chip μ-RTG**
Power	280W	40 mW	**1 – 100 mW**
Sp. Power	5 W/kg	8 μW/mm^3	**~ 1mW/mm^3**

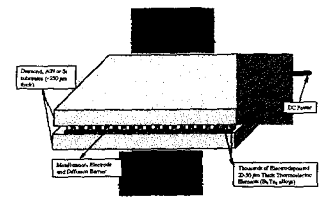


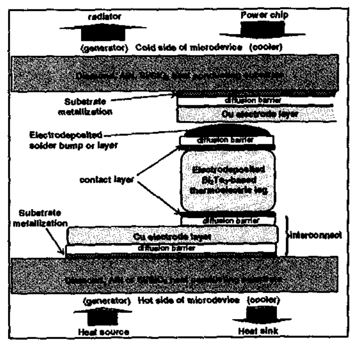
TE Microdevice Development

Electrochemical Deposition for Thermoelectric Microdevices

➢ ***Key challenges for TE microdevice fabrication***

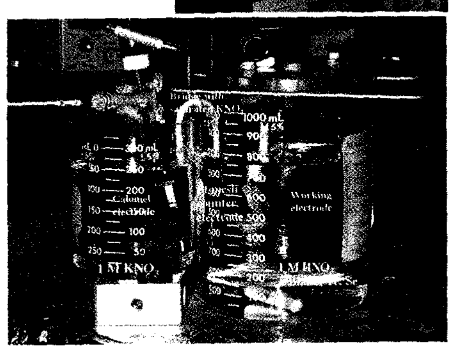
- Electrochemistry
  - **n-type and p-type $Bi_{2-x}Sb_xTe_3$ deposition**
  - **Optimization of thermoelectric properties**
  - **Morphology and stress control of semiconducting and metallic electrodeposits**
- Photoresist (PR):
  - **High aspect ratio patterns in up to 75 μm thick PR**
  - **Multiple processing of PR layers**
  - **Post-fabrication removal of processed thick PR layers**
- Legs and interconnects
  - **Adhesion between metal and semiconductor layers**
  - **Removal of metallic layers without damage to semiconductors**
  - **Alignment between multiple fabrication steps**
  - **Mechanical strength and resistance to high temperature anneals**





TE Microdevice Fabrication

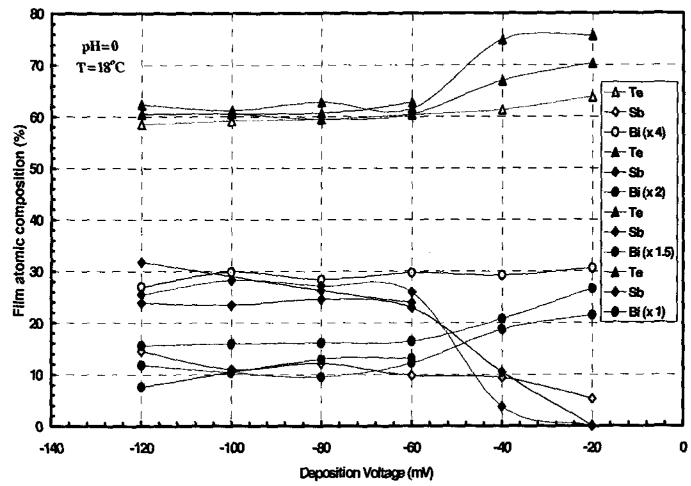
- An attractive route to deposition of thick films of TE materials
  - **High deposition rate on metallic substrates**
  - **Room temperature process, inexpensive,and scalable**
- $Bi_{2-x}Sb_xTe_{3-y}Se_y$ deposition
  - $13H^+ + 18e^- + 2BiO^+ + 3HTeO_2^+ \rightarrow Bi_2Te_3\downarrow + 8H_2O$
  - **JPL using potentiostatic control**
    - **Manual, computer-controlled equipment**
  - **Many process parameters**
    - **Deposition voltage, current [Bi] concentration, [Bi]/[Te] ratio...**
    - **Deposition setup, stirring rate, substrate quality, pH, temperature**
- Deposition of other metallic layers
  - **Cu, Ni, Pt, PbSn solder...**
- Up to 11,000 legs grown using a 30 μm pitch
  - **In 3x3 mm² area**



➢ *Process offers tremendous flexibility for configuring microdevices*

ECD of Ternary $Bi_{2-x}Sb_xTe_3$

Influence of Sb and Bi concentrations on Ternary $Bi_{2-x}Sb_xTe_3$ Film Composition



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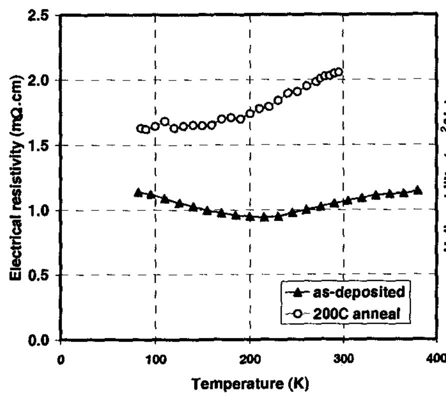
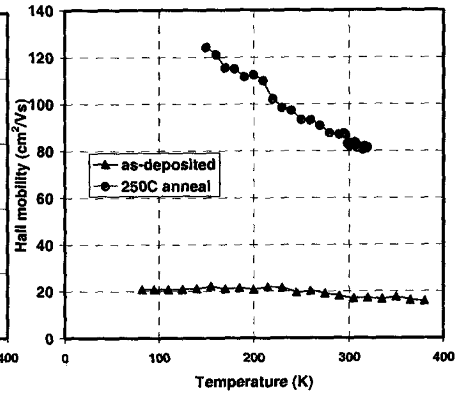
TE Properties Bi_2Te_3 Alloy Films

- As-deposited $Bi_2Te_{3-x}Se_x$ films
  - **Show heavily doped n-type behavior**
    - **S = -40 to -60 µV/K; (cross-plane measurement)**
    - **ρ ~ 1 mΩ.cm; n ~ 1×10^{20} cm^{-3}; μ_H ~ 15-25 $cm^2V^{-1}s^{-1}$ (in-plane measurement)**
    - **λ = 11 mW/cmK ;
(AC calorimetry in-plane measurement, 3-w measurement underway)**
- Electrical properties are improved by anneals
  - **Doping levels decrease and carrier mobilities increase**
    - **S up to -200 µV/K after 250°C anneal**
    - **ρ = 2-3 mΩ.cm; μ_H up to 80 $cm^2V^{-1}s^{-1}$ (in-plane measurement)**
- As-deposited $Bi_{2-x}Sb_xTe$ films
  - **As deposited: Seebeck values range from -60 to +250 µV/K**
  - **Seebeck values highly sensitive to film stoichiometry**
    - **Excess Te, Bi/Sb atomic ratio**
  - **Heat treatment study**
    - **Anneals in 200 to 300°C range improve p-type character of films**
    - **As for n-type, annealing of defects with donor-like behavior**
- More work to be done to complete characterization
  - **Film-level and device-level measurements**

ICT2001

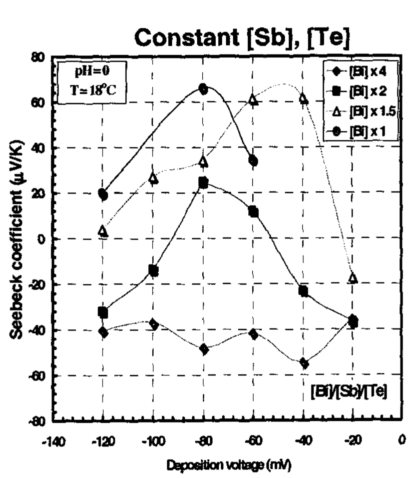
TE Properties Bi_2Te_3 Alloy Films

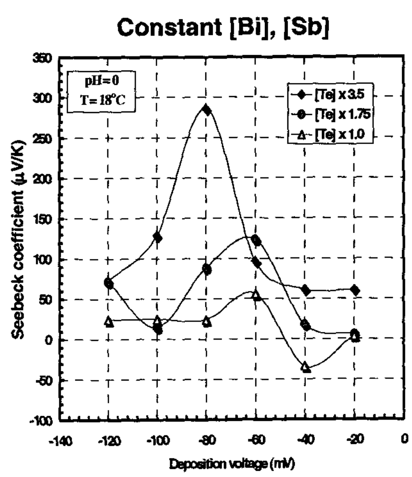




ICT2001

Properties $Bi_{2-x}Sb_xTe_3$ Alloy Films

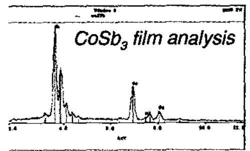


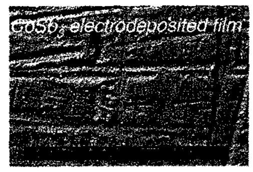


ICT2001

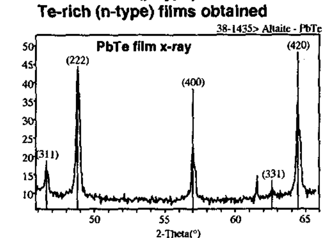
ECD of other TE Materials

- Exploring practical approaches to the electrodeposition of attractive TE materials for high temperature operation
  - **PbTe and its alloys**
    - **Also PbTe-Bi_2Te_3 based layered compounds**
  - **Skutterudites such as $CoSb_3$**





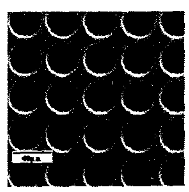
- Experimental results to date on PbTe
  - **Also using acidic PbTe aqueous solution**
    - **Pb+Te codeposition in -130 to -400 mV vs. SCE range**
    - **Both Pb-rich (p-type) and Te-rich (n-type) films obtained**

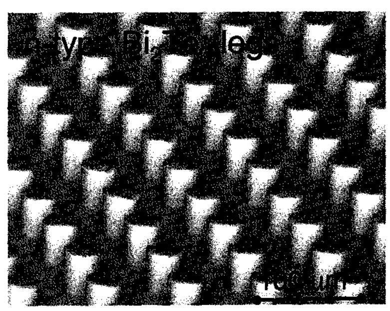


- Experimental results to date on $CoSb_3$
  - **Near neutral Co/Sb aqueous electrolyte at room temperature**
    - **Chelating agents**
  - **Codeposition of Co and Sb**
    - **From same bath**
    - **Some deposition conditions lead to mostly $CoSb_3$ phase**
    - **Characterization under way**

Electrochemically Deposited Bi_2Te_3 Legs Using Thick Photoresist Templates

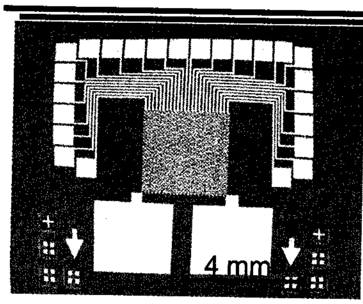
Photoresist template (top)

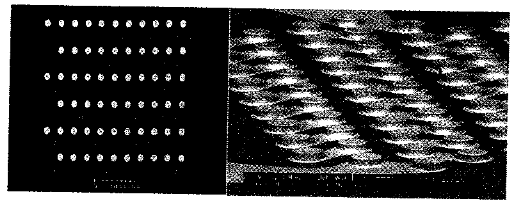




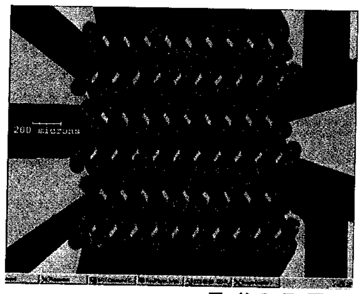
Photoresist template (side)

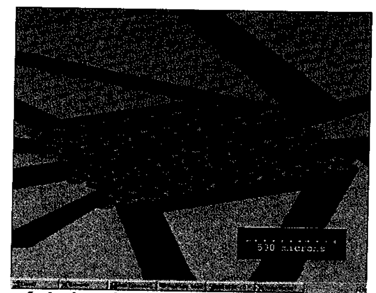
TE Microdevice Fabrication





TEMD Patterned metallizations, interconnects and legs

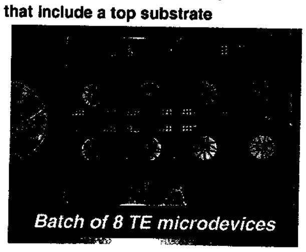




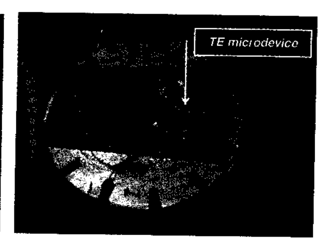
Full 3-D TEMD structure fabrication

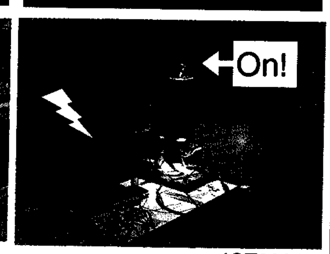
TE Microdevices: First demonstration

- TE microdevice fabrication status
  - **Many 3-D TE microdevice structures have been fabricated**
    - **Most of them have one set of n-type Bi_2Te_3 legs and one set of metallic legs**
  - **First 3-D structures with sets of n-type and p-type legs now being fabricated**
    - **Also working on full device that include a top substrate**
- First TEMD demos
  - **n-Bi_2Te_3/Au devices**
  - **Devices heat-treated at elevated temapratures**
  - **Heated on top by lamp**
  - **Small amount of power generated**
    - **From each string of 22 legs**
  - **String resistance as low as 2Ω**
    - **Means that contact resistivity between interconnects and Bi_2Te_3 is ~ 10^{-7} Ω.cm² or lower**
    - **More precise measurements will be made soon**

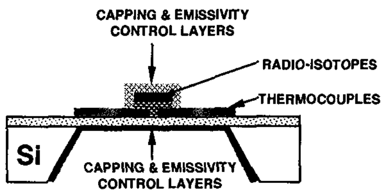


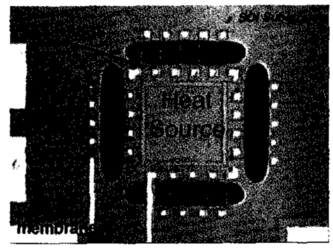
Batch of 8 TE microdevices

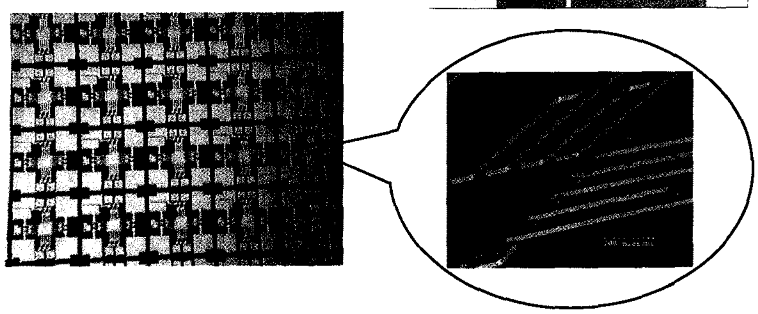




"μ-ARPS" In Plane TEMG Configurations







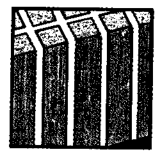
In-Plane TE microgenerator ECD/MEMS Fabrication on SOI

TE Nanodevice Development

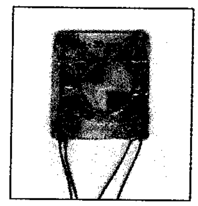
Nanowire Thermoelectric Generator

- **Proof-of-principle microdevice for a high performance microscale nanowire-based thermoelectric generator**
  - Nanowires as TE legs with 20 nm diameter and 50 to 60 µm height
    - Using anodized alumina templates
    - Using conventional microelectronics processing techniques
    - Quantum confinement, interface scattering could lead to 4-5% efficiency at $\Delta T = 50K$
    - High power density from thousands of legs
      - >> 1000,000 in 1 cm^2
      - Open Circuit Voltage > 100 V for $\Delta T = 50K$
- Experimental results to date
  - Grew n-type Bi_2Te_3 and p- type $Bi_{2-x}Sb_xTe_3$ nanowires electrochemically
    - Up to 60 µm long
  - Developed methods for processing nanowires
    - Electrodeposited 10-20 nm x 40 µm Bi_2Te_3 elements
  - Conducting studies to make 10 nm alumina templates
  - Measured some thermoelectric characteristics of n-type Bi_2Te_3 wires
    - Seebeck Coefficient as high as -125 µV/K
  - Initiated collaborations with various universities

- For energy harvesting application
  - Energy harvesting of rejected heat in various structures to increase overall efficiency, autonomy
    - Rejected heat on solar arrays, small spacecraft
  - Power for microdevices
    - High voltage even with small ΔT
    - Power for science instruments, sensors, SOAC
  - Other waste heat recovery applications

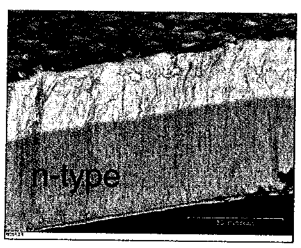


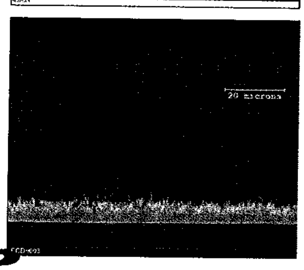
Nanowire-based, small ΔT, high voltage microgenerator (concept)



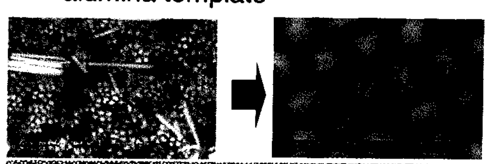
Electrodeposition into Nanostructured Templates

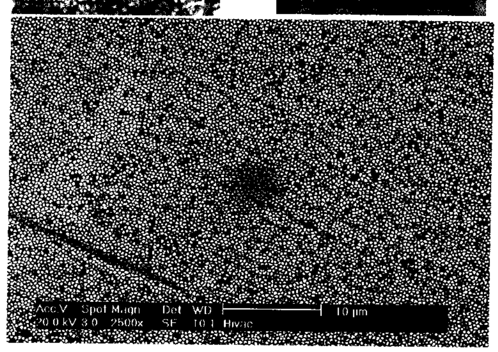
- Both n-type and p-type $Bi_{2-x}Sb_xTe_3$ nanowires





- Polished top surface of Bi_2Te_3 nanowires filling an anodized alumina template





TEMDs: Summary

- Many applications available if thermoelectric microdevices can successfully demonstrate predicted performance

- Waste heat recovery and spot cooling are promising areas
  - Microgenerators and microcoolers for integration with electronics
    - New technology based on electrochemistry of SOA materials
    - Batch fabrication possible
    - Technology and lessons learned could later be used for application of low dimensional structures in TE devices

- SOAC-like technical approach for use of TE micro/nanodevices
  - Distributed architecture for power thermal management where it is needed
    - Enhanced autonomy, reliability
    - Modular, scalable technology: ECD, CVD, IC, MEMS
  - Embedded, rugged power sources:
    - Waste heat, energy harvesting, combustion, radioisotope heat sources
    - High specific power could be possible: mW/mm^3 capability
    - Hybrid conversion and conversion/storage solid-state systems
  - Integrated cooling/thermal management
    - Cooling device fabrication and integration technology compatible with electronics/optoelectronics
    - Hybrid cooling technologies